Planetary Defense Conference 2013
Flagstaff, AZ, USA
IAA-PDC13-04-25
Lower Limits on NEO Deflection Velocities from Melt and Vapor Blow-off Momentum☆

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Abstract

For Earth-impacting objects that are large in size or have short warning times nuclear explosives are an effective threat mitigation response. Nuclear-based deflection works via conservation of momentum: material is heated and ejected from the body imparting momentum to the remaining mass. Predicting the response of a particular object is difficult, since the ejecta size and velocity distributions rely heavily on the unknown, complicated internal structure of the body. However, lower bounds on the blow-off momentum can be estimated using the melted/vaporized surface material. In this paper, we model the response of a one-dimensional SiO_2 surface to a standoff neutron fission-weapon detonation using Arbitrary Lagrangian-Eulerian radiation/hydrodynamic simulations. Errors in the blow-off momentum due to our hydrodynamic mesh resolution are quantified and inform zone sizing that balances interpolation error with computational efficiency. We find a mesh resolution of $\sim$ 0.5 cm in size down to a minimum depth of $\sim$ 65 cm to be practical for simulations with incident energy densities less than or equal to 70 kJ/cc (based on a desired interpolation error of $< 10\%$). Using these mesh constraints, the response of our one-dimensional SiO_2 surface to a standoff neutron fission-weapon detonation is simulated, and lower bounds are placed on the melt/vapor blow-off momentum as a function of incident energy density.

Keywords: deflection, nuclear explosive, hydrodynamic simulation, momentum transfer

1. Introduction & Background

Large asteroid and comet collisions with Earth represent a low-probability but potentially high-consequence threat. The devastation from a collision with a potentially hazardous object

☆LLNL-PROC-633312. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and partially funded by the Laboratory Directed Research and Development Program at LLNL under tracking code 12-ERD-005.

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(PHO) ranges from localized disasters to global extinction. Estimates place the chance of being struck by a small PHO over the course of the next century as high as 30% Ref. [1]. Orbit tracking predicts that at least 400 PHOs will come within 20 lunar distances of the Earth over the next century, with more than two dozen with diameters greater than 150 meters (1/10 mile)[1].

While a suite of methods have been proposed to deflect PHOs, the use of nuclear explosives is the most effective means of diverting a PHO, at a rate 10-100 times more effective than non-nuclear alternatives Ref. [2]. For scenarios in which there is little warning time before impact or if the PHO is large, nuclear explosives may be the only option. Therefore, understanding precisely how these objects respond to nuclear explosions is critical.

In this paper, the lower bounds on NEO blow-off momentum from a nuclear device are explored. The NEO is modeled as a one-dimensional column of SiO_2 in order to study energy coupling to the material, the sensitivity of the hydrodynamic mesh to resolution, and the minimum amount of momentum transferred as a function of incident energy density. We chose an SiO_2 composition as an initial idealization. Its high melting and vaporization temperatures provide a reasonable lower limit on momentum transfer for a generic NEO scenario. Further studies with more representative compositions will follow at later time.

2. Energy Coupling

Most of the energy output in a nuclear detonation comes in the form of neutrons and photons. Here, the one-dimensional effects on SiO_2 from a fission-weapon neutron spectrum (Ref. [3]) are investigated (see Fig 2). Realistically, neutrons take a finite time to penetrate the surface and in-

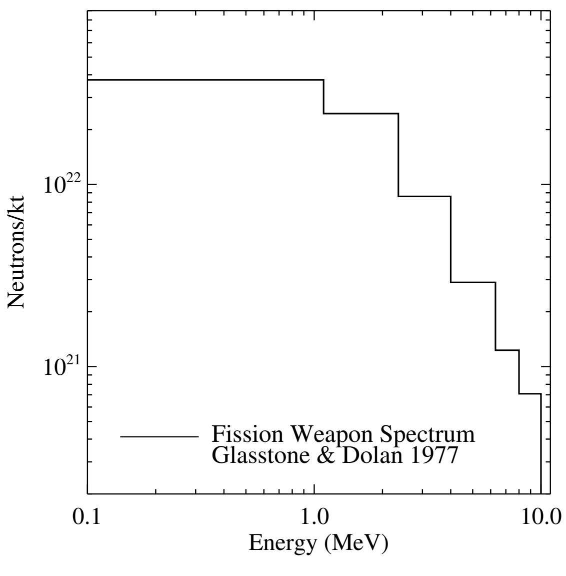

Figure 1: Neutron spectrum for a fission-weapon per kiloton total energy yield Ref. [3].

[1]Based on data obtained from the IAU Minor Planet Center, http://www.minorplanetcenter.net/

teract with the material. However, the timescales associated with energy deposition are extremely short compared to those for hydrodynamic motion. As an initial approximation, we neglect this shorter timescale and instead couple the energy directly to the material before simulating the surface response. Energy deposition into the material is approximated using a single characteristic deposition length, λ_d, that models the deposition of the Ref. [3] fission-weapon neutron spectrum into SiO_2, as determined by Ref. [4] simulations using TART, a Monte Carlo particle transport and collision code developed at Lawrence Livermore National Laboratory. Ref. [4] measures λ_d = 33 cm in SiO_2 for the Ref. [3] fission-weapon neutron spectrum.

In two-dimensions, the energy couples to a spherical object approximately as (Ref. [4]),

$$\epsilon_{dep}(r,\theta) = \epsilon_0 \exp\left[-\frac{(R-r)}{\lambda_d}\right]\cos\frac{\pi\theta}{2\theta_t} \tag{1}$$

where r and θ are the radius and angle at which energy is being deposited, respectively, ϵ_0 is the incident energy density at the surface of the NEO, R is the radius of the NEO, λ_d is the characteristic deposition length as measured by TART, and θ_t is the maximum angle of incidence as measured from the center of the NEO (see Fig 2 for an illustration). While an approximation,

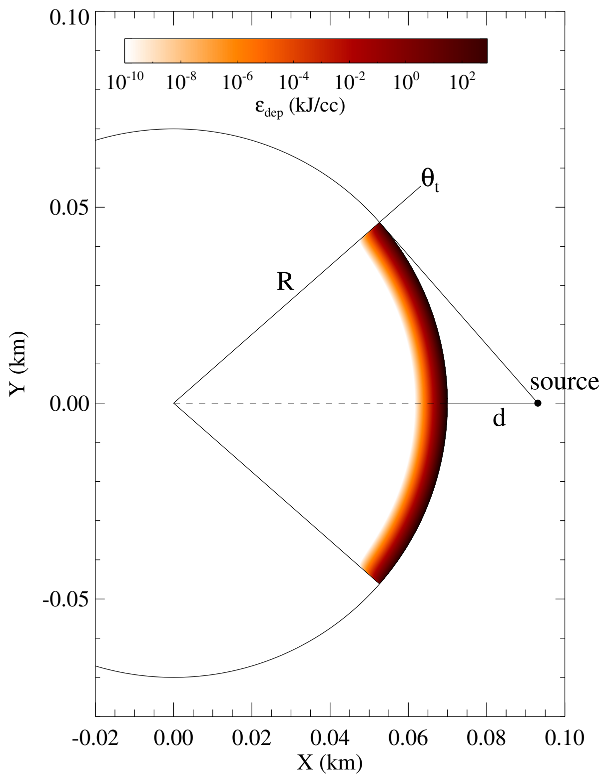

Figure 2: Illustration of energy coupling to an NEO. Ref. [3] fission-weapon neutrons are deposited into a two-dimensional, 70 meter diameter, SiO_2 NEO using Eq 1. (Note, any apparent lack of variation with θ is due to the logarithmic color scale.)

this is accurate to leading order, and is highly convergent in subsequent orders with systematic errors from neglected terms at the sub-one percent level. For one-dimension, evaluating Eq 1 on axis simplifies to,

$$\epsilon_{dep}(r) = \epsilon_0 \exp\left[-\frac{(R-r)}{\lambda_d}\right]. \quad (2)$$

3. Resolution

We model our one-dimensional asteroid using the hydrocode ARES, an Arbitrary Lagrangian-Eulerian radiation hydrocode (ALE rad/hydro) developed at Lawrence Livermore National Laboratory using the Livermore Equation of State (LEOS) for SiO_2. LEOS is a tabular library that provides thermodynamic function data over a wide range of temperature and density values.

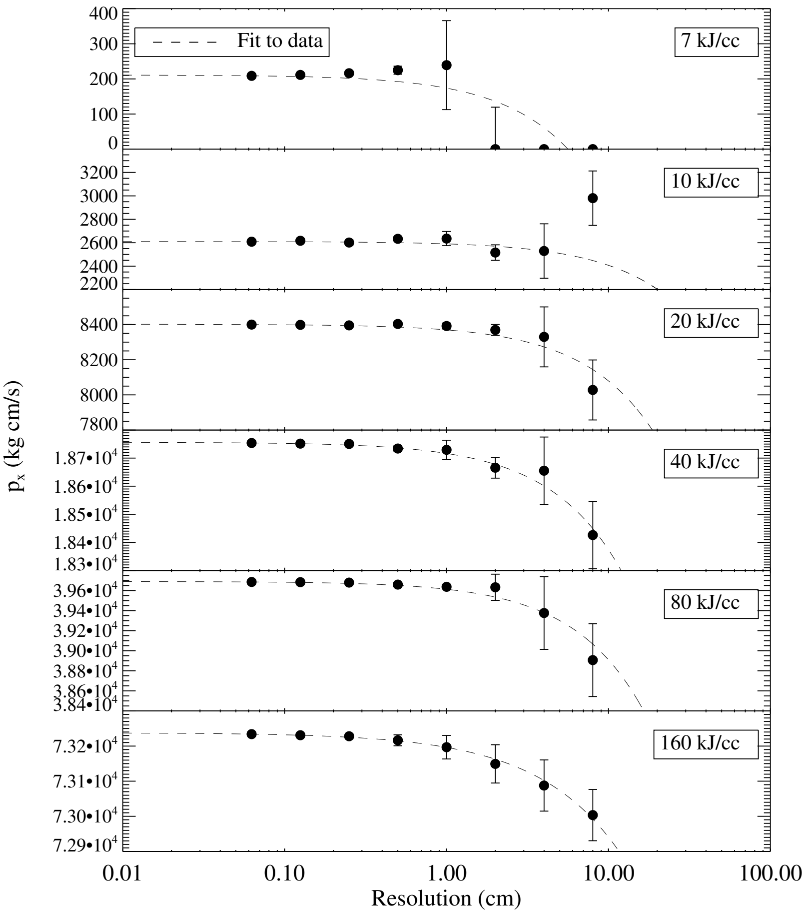

Figure 3: Blow-off momentum as a function of hydro mesh resolution. Interpolation errors are approximated as the difference between each blow-off momentum value and its neighboring point. The asymptotic blow-off momentum value at each energy density is estimated by fitting a power law function plus a constant ($ax^b + c$).

Two key outputs of the ARES simulations are the mass and momentum of the melted and vaporized material. The accuracy of these outputs depends on mesh resolution. Constructing a mesh that both adequately resolves the problem to curtail interpolation errors and minimizes the overall number of zones to conserve computing resources is desirable, particularly for extending our simulations to two- and three-dimensions. The effects of mesh zone size are investigated by measuring the blow-off momentum of the melted and vaporized material as a function of incident energy density (ϵ_0) and zone size (Δr). The blow-off momentum is defined by material that has been melted or vaporized according to the LEOS, and has a velocity greater than the escape velocity, based on a spherical representation of the object. Because material can recondense in space, once a zone has been a melted/vaporized and ejected from the surface of the NEO it retains its status as blow-off for the purpose of the momentum calculation, regardless of future phase changes. In three-dimensions, the melt/vapor blow-off momentum can be used to calculate a lower limit deflection velocity by dividing by the remaining NEO mass.

A variety of scenarios ranging in energy densities (7 kJ/cc $\leq \epsilon_0 \leq$ 160 kJ/cc) and zone sizes (0.0625 cm $\leq \Delta r \leq$ 8 cm) are simulated to explore the affect of zone resolution on the final blow-off momentum. The results are shown in Fig 3. Interpolation errors are approximated as the

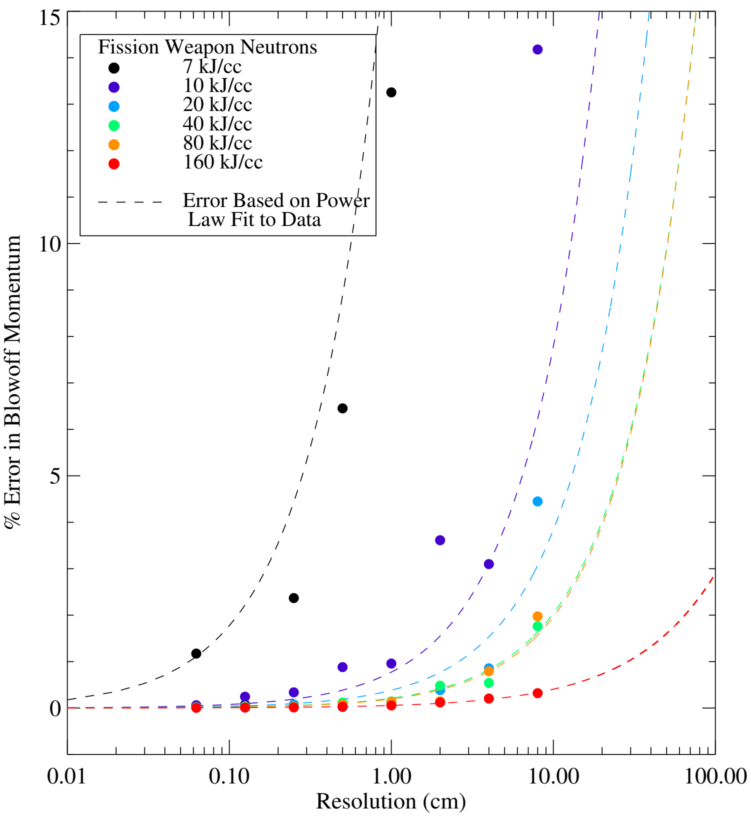

Figure 4: Interpolation errors in the blow-off momentum as a function of mesh resolution. Solid points show the percent error in the simulated data points (colored by incident energy density), where the asymptotic blow-off momentum value is determined by fitting a power law function plus a constant to the weighted blow-off momentum values (solid points in Fig 3). The dashed lines show the percent error predictions based on power law fits to data (dashed line in Fig 3).

difference between each blow-off momentum value and its neighboring point. Since traditional convergent behavior is often observed to follow a power law form, we fit a power law function plus a constant ($ax^b + c$) to the simulated points weighted by error to estimate an asymptotic blow-off momentum value at each energy density. Using the power law fits, errors in the blow-off momentum as a function of mesh resolution can be approximated. Scenarios involving lower energy densities are found to require higher mesh resolution. These results are show in Fig 4. Based on an desired error of $< 10\%$, a reasonable resolution for the fission-weapon neutron source is determined to be $\Delta r = 0.5$ cm.

4. Blow-off Momentum

The one-dimensional blow-off momentum is measured as a function of incident energy density for the Ref. [3] fission-weapon neutron spectrum on a SiO_2 column using a mesh resolution of $\Delta r = 0.5$ cm, and the results are plotted in Fig 5 (top). Changes in escape velocity due variations in the object size negligibly affect the results, since the final blow-off momentum is dominated by the fast moving material closest to the surface. Below an incident energy density of $\epsilon_0 \sim 6.9$ kJ/cc there is no momentum transfer, since energies are so low that both no material is vaporized and any melted zones have velocities significantly less than escape velocity. These results are consistent with what is expected based on the enthalpy of fusion Ref. [5] and vaporization Ref. [6] for SiO_2, which requires energy densities of at least $\epsilon_{\mathrm{melt}} \sim 5$ kJ/cc and

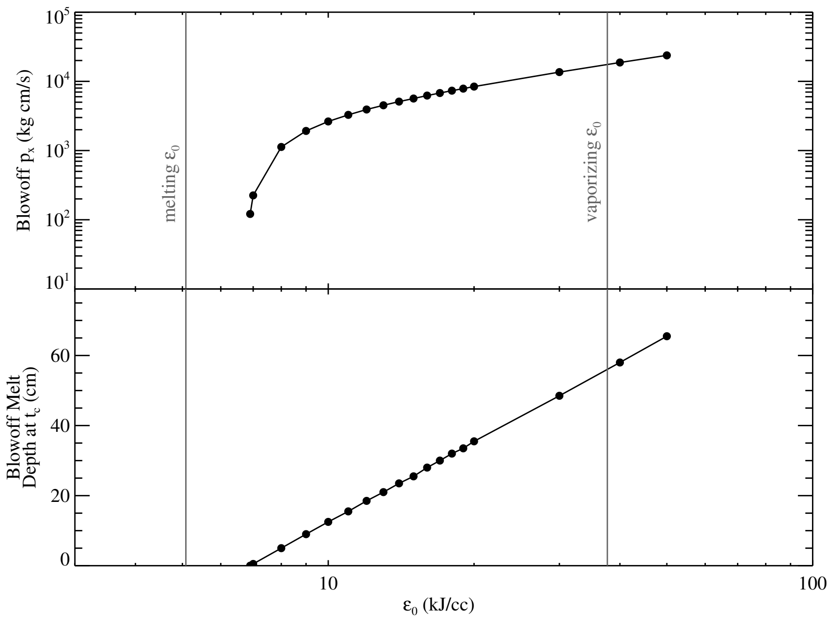

Figure 5: Blow-off momentum (p_x) and melt depth at the time the blow-off momentum asymptotic value is reached for the melted/vaporized material that will escape for a one-dimensional SiO_2 column with a radius of 70 meters, density of 2.65 g/cc, and a mesh resolution of 0.5 cm. Over plotted are the enthalpy of fusion, 145 MJ/kg Ref. [5], and enthalpy of vaporization, 11.77 MJ/kg Ref. [6].

$\epsilon_{vapor} \sim 30$ kJ/cc, respectively.

As discussed in § 3, it is important to construct a mesh with zone sizes small enough to adequately resolve the problem, while minimizing the overall number of zones to conserve computing resources. At the end of each simulation run, zones that are melted/vaporized and ejected from the surface are tagged, and the original depth of the zone at $t = 0$ is determined. Beyond this depth, material that is melted does not reach a velocity greater than escape velocity and contributes nothing to the final blow-off momentum value. This value is instructive for determining the depth to which higher resolution zoning is needed. Fig 5 (bottom) shows that a higher mesh resolution is needed down to a depth of ∼ 65 cm for our highest incident energy density run of 70 kJ/cc.

5. Conclusions

Lower bounds are placed on the blow-off momentum from a fission weapon neutron device incident on a one-dimensional SiO_2 column. Below an energy density of ∼ 6.9 kJ/cc there is no momentum transfer. We find interpolation errors of $< 10\%$ for mesh resolutions < 0.5 cm. For simulations with incident energy densities < 70 kJ/cc, higher resolutions are needed down to a depth of ∼ 65 cm to ensure accurate results. These results will be used to inform future one-, two- and three-dimensional simulations modeling the surface response of NEOs of varying compositions to an assortment of photon and neutron sources.

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